On the Synchronization Stability of Converters connected to Weak Resistive Grids

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***Abstract*—The paper proposes a simplified yet accurate converter model for the analysis of the synchronization stability considering the effect of weak resistive grids. A thorough comparison with simulations obtained with detailed EMT models shows that the proposed model captures precisely the synchronization transients. Simulation results also indicate that the impact on synchronization stability of the resistances of the grid on the synchronization stability depends on the state of the converter operation.**

***Index Terms*— Synchronization stability, converter-interfaced generator (CIG), phase-locked loop (PLL).**

I. INTRODUCTION

With a migration to a higher renewable penetration grid, the synchronous generators are gradually replaced by converter-interfaced generation [1,2]. The dynamic response of a power system with high renewable penetration is dominated by the operation and control of these converters. Converter-interfaced generators (CIGs) shall no longer disconnect from the grid during the fault but have to maintain the power generation to avoid further contingencies or even blackout due to the wide loss of generation [3]. Thus, the ability of the low voltage ride-through is critical for a stable CIGs operation. However, during a severe grid fault, the converter may still suffer loss of synchronization and become unstable even if the low voltage ride through (LVRT) requirements are satisfied [4]. For example, this has been highlighted by the British transmission system operator (TSO), National Grid, which indicated that the risk of the loss of the synchronization stability of the phase locked-loop (PLL) based converters is rising during faults in a weak grid [5]. In this context, an accurate model of the CIG synchronization stability is a pre-condition to analyze the mechanism of its grid synchronization and to robustly design the CIG controller for the enhancement of its stability. In particular, this paper considers the impact of network losses on the synchronization stability, an aspect that has not been fully studied so far.

The study of different types of PLLs has already been thoroughly investigated, yet only considering its grid-synchronization loop in a strong grid, for which the voltage at the point of common point (PCC) is assumed to be fixed and invariable to the grid power injection from the CIG [6]. However, if the grid is weak, i.e., lines have a non-negligible inductive component, the PCC voltage is no longer stiff but couples to the CIG grid power injection and results in the possibility of synchronization instability. In order to analyze this phenomenon, a static model identifying the equilibrium point of the CIG operation with respect to the grid state was presented in [7,8]. It shows that the allowable LVRT of the CIG depends on the grid impedance and the reactive current injection at the PCC. Since this model is static, the proposed stability criteria are only necessary but not sufficient. The CIG may lose synchronization stability during the transition to the equilibrium point. To capture this transient response, a Quasi-Static Large-Signal (QSLS) model was proposed in [9]. This model clearly shows that the positive feedback from the self-synchronization loop worsens the PLL dynamics. Based on this model, reference [10] illustrated the equivalence of the PLL dynamics to the synchronization mechanism of the synchronous generator. Hence, the equivalent damping and inertia of the PLL is identified. Referring to the stable region of the SG, reference [11,12] used phasor analysis and numerical approximations to estimate the PLL stable region. Reference [13] compares these methods [9-13] and verifies that the QSLS is more precise than other methods.

In the literature, a second-order QSLS model has been widely utilized to assess the synchronization stability of multi-converter systems [14] and unbalanced systems [15]. The differential equations of this model take into account only the PLL dynamics, since the converter is assumed to be an ideal current source. However, in practice, CIGs are commonly based on voltage-sourced converters, which is essentially a voltage source, which thus, has transients on the current control. Reference [16] proves that the dynamics of these currents can worsen the synchronization stability and modifies the QSLS model by including a current dynamics loop. However, this model is based on the inductive grid impedance, while some of the CIGs are implemented in the distribution system which has a non-negligible resistive component in the impedance. The grid resistance changes the power flow in the system, couples the active and reactive power, and increases the system damping, thus has an impact on the synchronization stability. To better capture the CIGs synchronization transients in the distribution system, this paper modifies the synchronization stability model in [16] and analyzes the effect of resistive grid impedance on the synchronization stability.

The remainder of the paper is organized as follows: Section II analyzes the effect of the grid states on the synchronization stability; Section III develops a model of the synchronization stability analysis considering the current transients and analyzes the effect of the grid resistance. Section IV verifies the accuracy of the model and shows the effect of the grid resistance on the synchronization stability in different situations while Section V draws the conclusion.

II. Effect of Grid States on Synchronization Stability

The grid-feeding converter is widely used in renewable generation, where is most commonly t controlled to behave like a current source. The synchronization of this converter relies on the PLL, which tracks the phase of the PCC voltage as shown in Fig. 1, where $v_g$is grid voltage and $l_g$is grid impedance. The control of the typical synchronous reference frame PLL (SRF-PLL) as shown in Fig. 2 aims to force the detected phase from the PLL δ_{pll} to track the phase of the fundamental component of PCC voltage δ_{pcc}, as follows:

$$v_q = V_{pcc}\sin(\delta_{pcc} - \delta_{pll}) \tag{1}$$

Equation (1) describes the q-axis component of the PCC voltage as detected by the PLL. When the phase is locked, i.e. $\delta_{pcc} = \delta_{pll}$, then the q-axis component of the PCC voltage at the fundamental frequency (1) should be zero. $v_q = 0$ is thus the condition for a successful converter synchronization.

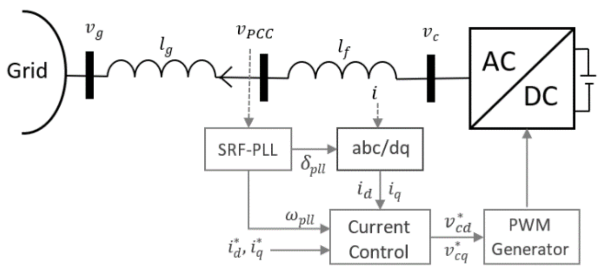

Fig. 1. Grid-Feeding Converter system structure

The analysis of (1) is the key to understand the synchronization stability. However, in the power system, only the grid voltage v_g is known and the PCC voltage is a consequence of the power flow through the grid impedance, which mainly depends on the state of the grid. Considering this, the modeling of the synchronization stability using (1) has to be extended correspondingly. This section models and analyzes the effect of the grid state on the synchronization stability.

A. Synchronization Stability in a Strong Grid

In a strong grid with a negligible grid impedance, i.e. $l_g \approx 0$, the PCC voltage always equals the grid voltage. Assuming the δ_{pcc} is the reference angle, i.e. $\delta_g = \delta_{pcc} = 0$, then, (1) can be rewritten as follows:

$$v_q = V_g sin(\delta_g - \delta_{pll}) = V_g \sin(-\delta_{pll}) \tag{2}$$

In this case, the synchronization stability (1) is solely depending on the grid-synchronization loop of the PLL with no influence from the grid state, i.e. Fig. 2. A proper $H(s)$ can ensure a solid synchronization. Hence, for the strong grid, the research concerning synchronization stability focuses on the design of the PLL controller [17].

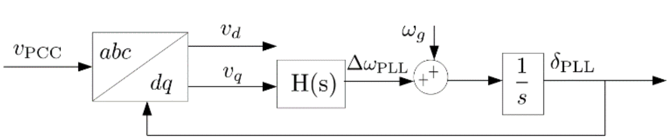

Fig. 2. PLL structure

B. Synchronization Stability in Weak Grid

In the case where the grid impedance is nonnegligible, i.e. weak grid, then the PCC voltage changes with the power flow. For a simple computation, assuming that δ_{pcc} is the reference angle, $\delta_g = -\delta_{pll}$. Then, (1) can be rewritten as follows:

$$\begin{aligned} v_q &= V_g \sin(-\delta_{pll}) + \omega_{pll} l_g i_d \\ &\approx V_g \sin(-\delta_{pll}) + \omega_{pll} l_g i_d^* \end{aligned} \tag{3}$$

where $\omega_{pll} = \omega_g + \Delta\omega_{pll}$ and $i_d^*$is the reference value of the d-axis component of the current, and $i_d = i_d^*$assumes perfect current tracking. In comparison with (2), besides the PLL grid-synchronization loop $V_g \sin(-\delta_{pll})$, the synchronization stability (3) in a weak grid has an additional self-synchronization loop represented by the term $\omega_{pll} l_g i_d$, which acts as a positive feedback in the overall synchronization loop, which thus worsens the synchronization stability as shown in Fig. 3. In the literature, grid-feeding converters are commonly assumed to be ideal current sources, $i_d = i_d^*$. Hence, the effect of the grid impedance is seen as a proportional gain and the total order of this model remains the same as when applied in the strong grid.

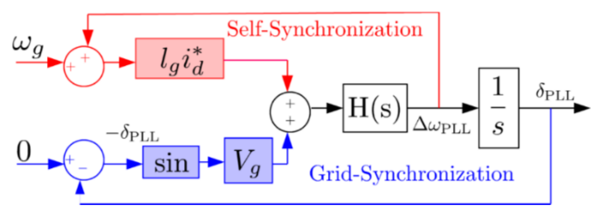

Fig. 3. Quasi-static large-signal model of the PLL

C. Synchronization Stability in a Distribution System

Small-capacity CIGs are generally connected to the distributed system, where line impedances have a non-negligible resistance r_g . Based on (3), the synchronization stability can be written as (4).

$$\begin{aligned} v_q &= V_g \sin(-\delta_{pll}) + \omega_{pll} l_g i_d + r_g i_q \\ &\approx V_g \sin(-\delta_{pll}) + \omega_{pll} l_g i_d^* + r_g i_q^* \end{aligned} \tag{4}$$

where $\omega_{pll} = \omega_g + \Delta\omega_{pll}$. In general, CIGs are supposed to compensate the reactive power to the grid during the LVRT, in which case the value of i_q is negative.

The following are relevant remarks based on (4):

- If $-r_g i_q < \omega_{pll} l_g i_d$, the phase angle δ_{pll} is positive. The capacitive current through the grid resistance $r_g i_q$ could partially cancel the positive effect of the $\omega_{pll} l_g i_d$ term on $V_g \sin(-\delta_{pll})$, thus widen the CIG operational range and increase the static voltage stability. This conclusion has been well verified by the previous literature [8].
- If $-r_g i_q > \omega_{pll} l_g i_d$, the phase angle δ_{pll} is negative. A further increase in $r_g i_q$ will enlarge the phase negatively thus degrade the converter stability.

- If $-r_g i_q > (V_g + \omega_{pll} l_g i_d)$, no equilibrium point exists. The converter is unstable.

III. Effect of the Current Transients on the Synchronization Stability

In the previous literature, the grid-feeding converter is assumed to be an ideal current source. The analysis of the synchronization stability only considers the PLL dynamics but neglects the current controller dynamics. This is because generally the time constant of the PLL is around 50-100 ms while that of the current controller is 0.5-5 ms [18]. However, in reality, the grid-feeding converter is a voltage source converter, for which the terminal voltage at the instant of the fault remains fixed resulting in an excessive fault current. Although the current controller can suppress this fault current within a few millisecond, the fault current may be much higher than the reference which enlarges the positive feedback $\omega_{pll} l_g i_d$, resulting in a larger δ_{pll} during the transient even converging into an unstable region. The converter may be unstable even if its QSLS model indicates stability, due to the effect of the current transients. Reference [16] added the loop of the current transients into the model (4) thus making its stability criteria become both sufficient and necessary. Based on the advanced model in [16], this section extends to consider the effect of the grid resistance on the synchronization stability.

A. Model of Current Transients On Synchronizatio Stability

Defining $\Delta i_d, \Delta i_q$ as the transient current change, i.e. $\Delta i_d = i_d^* - i_d$ and $\Delta i_q = i_q^* - i_q$ and substituting these into (4) gives:

$$\begin{aligned} v_q &= V_g \sin(-\delta_{pll}) + \omega_{pll} l_g (i_d^* + \Delta i_d) + r_g (i_q^* + \Delta i_q) \\ &= V_g \sin(-\delta_{pll}) + \omega_{pll} l_g i_d^* + \omega_{pll} l_g \Delta i_d + r_g i_q^* + r_g \Delta i_q \end{aligned} \quad (5)$$

Compared to (4), the transient current change includes another two loops for the transients of the Δi_d and Δi_q in the model. Now, the synchronization stability couples to both active and reactive current. The d-axis voltage at the PCC is given by:

$$\begin{aligned} v_d &= V_g \cos(-\delta_{pll}) - \omega_{pll} l_g (i_q^* + \Delta i_q) + r_g (i_d^* + \Delta i_d) \\ &= V_g \sin(-\delta_{pll}) - \omega_{pll} l_g i_q^* - \omega_{pll} l_g \Delta i_q + r_g i_d^* + r_g \Delta i_d \end{aligned} \quad (6)$$

During the fault, the PCC voltage changes along with the state of the fault, while the converter terminal voltage is the consequence of the current controller actions. The transient current is attributed to the voltage difference between the PCC and converter terminal voltage dropped across the filter:

$$i_d = \frac{v_{cd} - v_d}{\omega_{pll} l_g} \quad (7)$$

$$i_q = -\frac{v_{cq} - v_q}{\omega_{pll} l_g} \quad (8)$$

where the converter terminal voltage is v_c and in line with the current it has a static and a transient component, i.e. $v_{cd} = v_{cd,0} + \Delta v_{cd}$; $v_{cq} = v_{cq,0} + \Delta v_{cq}$. The static component is attributed to the reference current:

$$v_{cd,0} = V_g \cos(-\delta_{pll,0}) - \omega_g (l_f + l_g) i_q^* + r_g i_d^* \quad (9)$$

$$v_{cq,0} = \omega_g l_f i_d^* \quad (10)$$

where $\delta_{pll,0} = \sin^{-1}((\omega_{pll} l_g i_d^* + r_g i_q^*)/V_{g,0})$ is the pre-fault phase. The transient component is attributed to the transient current change, or the current error, $\Delta i_d = i_d^* - i_d$ and $\Delta i_q = i_q^* - i_q$, and arises only after the current controller acts :

$$\Delta v_{cd} = K_{pc} \Delta i_d + \int K_{ic} \Delta i_d - \omega_{pll} l_f \Delta i_q \quad (11)$$

$$\Delta v_{cq} = K_{pc} \Delta i_q + \int K_{ic} \Delta i_q - \omega_{pll} l_f \Delta i_d \quad (12)$$

Equations (5-12) represent the model of the synchronization stability of the grid-feeding converter. Fig. 4 shows the model structure. In comparison with the QSLS model, this model includes additional loops for the current transients and thus elevates the order of the model to be 4th order.

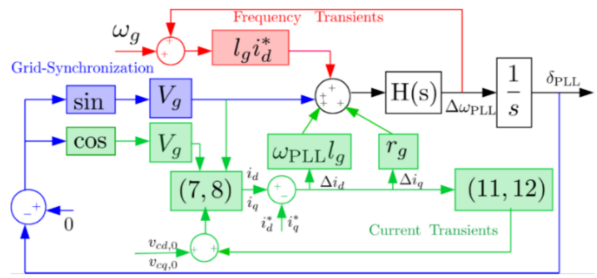

Fig. 4. Model of synchronization stability analysis considering the current transients and grid resistance

B. Analysis of Grid Losses on Synchronization Transients

The effect of the grid resistance on the QSLS synchronization transients, i.e. (4) has been described in Section II-C. In addition, the grid resistance also affects the current transients as indicated in (5~10), which will have an impact on the synchronization stability.

At the instant of the fault $t = 0^+$, the converter terminal voltage remains invariant as described by (9,10), approximately at the nominal value. At the occurrence of the fault, the grid voltage sags from V_g to $V_g - \Delta V_g$, thus instantly lowering the PCC voltage. The voltage difference between the converter terminal and grid at this moment is significant, thus, resulting in a peak current. Substituting (9,10) and the grid voltage change ΔV_g into (5-10) gives the resulting transient current change at the peak:

$$\Delta i_{d,0^+} = \frac{\Delta V_g \cos(\delta_{pll,0})}{\omega_g l_f} \quad (13)$$

$$\Delta i_{q,0^+} = -\frac{\Delta V_g \sin(\delta_{pll,0})}{\omega_g l_f} \quad (14)$$

If the transients from the impedance ($L\frac{di}{dt}$) are neglected, (13) and (14) indicate that the peak current is solely related to the filter inductance. The *d*-axis current increases at the instant of the fault whatever the initial state of the system, which worsens the synchronization transients when $\delta_{pll,0} > 0$ while improving it when $\delta_{pll,0} < 0$ as indicated before in (4). On the other hand, the *q*-axis current change and the initial phase present a negative correlation. As analyzed in Section II-C, the negative increase in *q*-axis current enhances the synchronization stability, thus, the transient q-axis current benefits the stability. Note, since the initial phase $\delta_{pll,0}$ normally is small, the current transients on d-axis is more significant than that on q-axis.

IV. Simulation Results

A real-time Electromagnetic Transients (EMT) simulation in Matlab/Simulink is used to validate the above analysis and specifically to verify following aspects:

- The accuracy of the proposed model for the synchronization stability analysis in comparison to the QSLS model;
- The impact of the current transients on the synchronization stability;
- The impact of the grid resistance on the synchronization stability.

The proposed model and QSLS model are built in Matlab/Simulink using only math blocks. The initial system is at nominal with 50 Hz,10 kV. The PI controller of the PLL has gains 0.022/0.392. A voltage sag occurs in the grid at 5 s from nominal to 0.32 pu.

A. Model Validation and Accuracy

Two cases are considered in this section to validate the accuracy of the proposed model: Case 1 has a small current transients with 0.1 ms current controller time constant, i.e. $l_f = 0.32\ H, K_{pc} = 3200, K_{ic} = 2433$; and Case 2 has a larger current transients with 0.5 ms current controller time constant, i.e. $l_f = 0.12\ H, K_{pc} = 240, K_{ic} = 486.6$. In both cases, $l_g = 0.2\ H, r_g = 5\ \Omega, i_d^* = 81.65A, i_q^* = -40.82\ A$. Figure 5 shows the transients of the PLL phase δ_{pll} and the converter output current in both d-axis and q-axis after the fault occurrence.

The proposed model can accurately capture the PLL behaviour during the transient in comparison with the result from the EMT model. Since it neglects current transients, the QSLS model presents the same response for both cases. In the case of $-r_g i_q < \omega_{pll} l_g i_d$, a larger current transient make the PLL lose synchronization and the converter becomes unstable after the fault. This is because the transient current in d-axis surges to above 100 A and causes the phase to move into the unstable region. After that, the current oscillates at the saturation frequency of the PLL.

B. Effect of $-r_g i_q < \omega_{pll} l_g i_d$

This scenario considers same parameters of the converter as those utilized in Case 1 of Section IV.A. Figure 6 shows the results for different grid resistances but ensuring that $-r_g i_q < \omega_{pll} l_g i_d$, i.e., 0 Ω, 5 Ω and 20 Ω. The negative reactive current through the grid resistance adds a negative feedback into the synchronization transients and results in a phase reduction in both transient and steady state. The inclusion of the grid resistance enhances the synchronization stability. Moreover, the grid resistance does not impact on the peak of the current as shown in Fig. 6 (b) at 5 s.

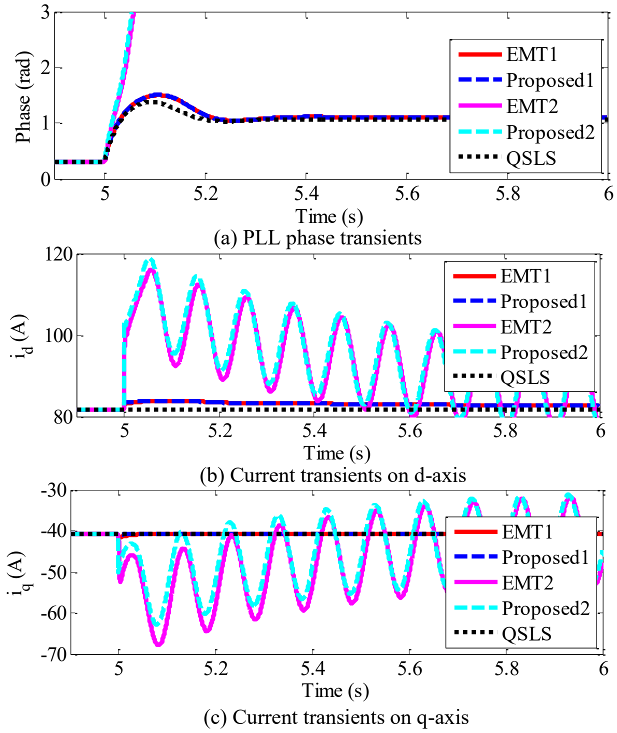

Fig. 5. Model Validation of synchronization stability assessment for two cases, Case 1: small current transient; Case 2: larger current transient.

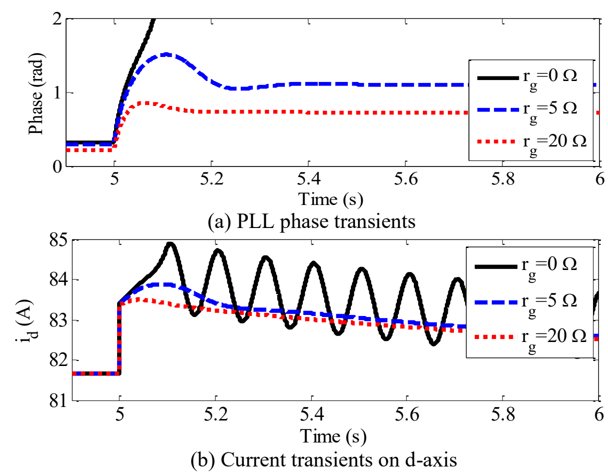

Fig. 6. Effect of $-r_g i_q < \omega_{pll} l_g i_d$ on synchronization stability.

C. Effect of $-r_g i_q > \omega_{pll} l_g i_d$

This scenario considers same parameters of the converter parameters as those considered in Section IV.B except for the current references, which are set to $i_d^* = 0\ A$; $i_q^* = -81.65A$ in order to ensure that $-r_g i_q > \omega_{pll} l_g i_d$. Figure 7 shows the results obtained with various values of the grid resistance. The initial phase becomes negative and the imposing of a negative feedback into the synchronization transients at both transients and steady-state due to the inclusion of the capacitance current through the grid resistance increases the phase negatively and reduces the stability margin.

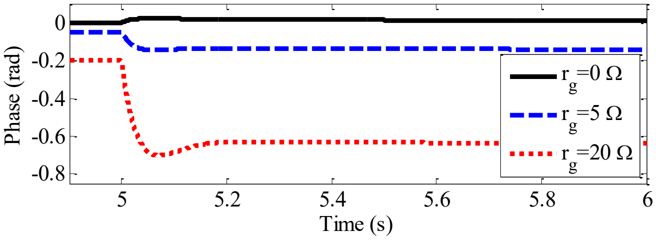

Fig. 6. Effect of $-r_g i_q > \omega_{pll} l_g i_d$ on synchronization phase transients.

D. *Effect of current transients at* $-r_g i_q > \omega_{pll} l_g i_d$

In this case, we repeat the tests carried out in Section IV.A but use the current references in Section IV.C to impose the condition $-r_g i_q > \omega_{pll} l_g i_d$. The grid fault now drops to 0.2 pu at 5 s. Figure 7 shows that, compared to the EMT model, the proposed model properly captures the synchronization transients, whereas the QSLS model fails. For $-r_g i_q > \omega_{pll} l_g i_d$, a larger current transient enhances the transient stability and even make an unstable system stable. This conclusion is opposite to that in a situation of $-r_g i_q < \omega_{pll} l_g i_d$. The grid resistance adds damping into the system thus slows down the phase change in comparison with Fig. 5 (a). This gives an extra time to clear the fault.

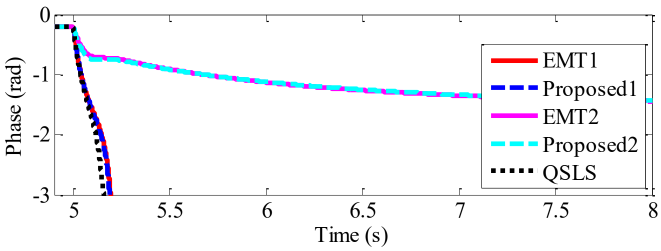

Fig. 7. Effect of current transients in the situation of $-r_g i_q > \omega_{pll} l_g i_d$

V. Conclusions

The paper proposes a simple yet accurate model to assess the synchronization stability of converters connected to weak resistive grids. The proposed model properly takes into account the transient behavior of the currents of the converter and approximates well the transient response of the fully-fledged EMT converter model. Simulation results indicate that the impact of the resistance of the lines to which the converter is connected is not negligible. A noteworthy conclusion of this work is that these resistances have a significant role in the synchronization stability. In particular, the transient behavior of the converter currents worsens if $-r_g i_q < \omega_{pll} l_g i_d$ and improves if $-r_g i_q > \omega_{pll} l_g i_d$. Future work will focus on the design of a converter current control that makes the synchronization stability independent from the impedance of the grid.

References

[1] F. Milano, F. Dörfler, G. Hug, D. J. Hill, and G. Verbič, “Foundations and challenges of low-inertia systems (Invited Paper),” in 20th Power Systems Computation Conference (PSCC), 2018.

[2] J. Chen, M. Liu, F. Milano and T. O’Donnell,” 100% Converter-Interfaced generation using virtual synchronous generator control: A case study based on the Irish system,” Electric Power Systems Research, 2020.

[3] B. Kroposki, B. Johnson, Y. Zhang, V. Gevorgian, P. Denholm, B. M. Hodge,and B.Hannegan, “Achieving a 100% renewable grid: Operating electric power systems with extremely high levels of variable renewable energy,” IEEE Power & Energy Magazine, vol. 15, no. 2, pp. 61–73, March 2017.

[4] O. Goksu, R. Teodorescu, C. L. Bak, F. Iov, and P. C. Kjær,“Instability of wind turbine converters during current injection to low voltage grid faults and PLL frequency based stability solution,” IEEE Transactions on Power Systems, vol. 29, no. 4, pp. 1683–1691, Jul. 2014.

[5] NationalGrid, UK, “Performance of phase-locked loop based converters,” Technical Report, 2017.

[6] P. Rodríguez, A. Luna, R. S. Muñoz-Aguilar, I. Etxeberria-Otadui, R. Teodorescu, and F. Blaabjerg, “A stationary reference frame grid synchronization system for three-phase grid-connected power converters under adverse grid conditions,” IEEE Transactions on Power Electronics, vol. 27, pp. 99–112, Jan 2012.

[7] I. Erlich, F. Shewarega, S. Engelhardt, J. Kretschmann, J. Fortmann, and F. Koch, “Effect of wind turbine output current during faults on grid voltage and the transient stability of wind parks,” in Proceedings of the IEEE PES General Meeting, pp. 1–8, July 2009.

[8] J. Chen, F. Milano and T. O'Donnell, "Assessment of Grid-Feeding Converter Voltage Stability," in IEEE Transactions on Power Systems, vol. 34, no. 5, pp. 3980-3982, Sept. 2019.

[9] D. Dong, B. Wen, D. Boroyevich, P. Mattavelli, and Y. Xue, “Analysis of phase-locked loop low-frequency stability in three-phase grid-connected power converters considering impedance interactions,” IEEE Transactions on Industrial. Electronics, vol. 62, no. 1, pp. 310–321, Jan. 2015.

[10] H. Wu and X. Wang, "Transient Stability Impact of the Phase-Locked Loop on Grid-Connected Voltage Source Converters," 2018 International Power Electronics Conference (IPEC-Niigata 2018 -ECCE Asia), Niigata, 2018, pp. 2673-2680.

[11] H. Wu and X. Wang, "Design-Oriented Transient Stability Analysis of PLL-Synchronized Voltage-Source Converters," in IEEE Transactions on Power Electronics, vol. 35, no. 4, pp. 3573-3589, April 2020.

[12] M. G. Taul, X. Wang, P. Davari, and F. Blaabjerg, “An efficient reducedorder model for studying synchronization stability of grid-following converters during grid faults,” in 2019 20th Workshop on Control and Modeling for Power Electronics (COMPEL), pp. 1–7, June 2019.

[13] M. G. Taul, X. Wang, P. Davari and F. Blaabjerg, "An Overview of Assessment Methods for Synchronization Stability of Grid-Connected Converters Under Severe Symmetrical Grid Faults," in IEEE Transactions on Power Electronics, vol. 34, no. 10, pp. 9655-9670, Oct. 2019.

[14] M. G. Taul, X. Wang, P. Davari and F. Blaabjerg, "Reduced-Order and Aggregated Modeling of Large-Signal Synchronization Stability for Multi-Converter Systems," in IEEE Journal of Emerging and Selected Topics in Power Electronics, 2020.

[15] M. G. Taul, S. Golestan, X. Wang, P. Davari and F. Blaabjerg, "Modeling of Converter Synchronization Stability under Grid Faults: The General Case," in IEEE Journal of Emerging and Selected Topics in Power Electronics, 2020.

[16] J. Chen, M. Liu, T. O'Donnell and F. Milano, "Impact of Current Transients on the Synchronization Stability Assessment of Grid-Feeding Converters," in IEEE Transactions on Power Systems, vol. 35, no. 5, pp. 4131-4134, Sept. 2020.

[17] A. Luna et al., “Grid voltage synchronization for distributed generation systems under grid fault conditions,” IEEE Transactions on Industrial Applications, vol. 51, no. 4, pp. 3414–3425, Jul. 2015.

[18] A. Yazdani and R. Iravani, “Voltage-soured Converters in Power Systems,” Wiley IEEE Press, 2010.